

AN EXPERIMENTAL STUDY OF
CHANNELING

BY
RAGNAR HELLBORG

LUND 1973

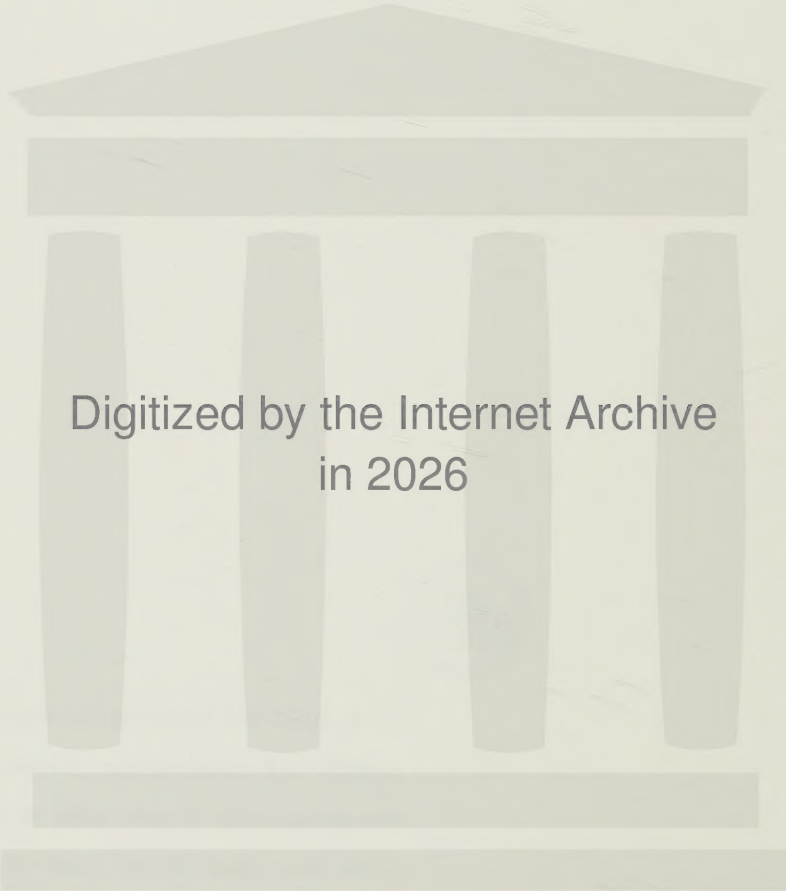
AN EXPERIMENTAL STUDY OF
CHANNELING

BY
RAGNAR HELLBORG

LUND 1973



to my Wife and Children for their
support and understanding during
the performance of this work which
often took place at odd hours and
during weekends.



Digitized by the Internet Archive
in 2026

https://archive.org/details/IA41552415_0038

THESIS

The present work deals with the channeling effect, mainly in diatomic crystals. The predominant requisite for the performance of this type of experimental study is access to a particle accelerator with variable ion energy and with high geometrical quality of the beam. In the experiments the Van de Graaff accelerators at Studsvik and Lund have been used. The work can be divided into three closely connected parts: The first one consists of four papers, all using the nuclear reaction $^{19}\text{F}(\text{p}, \alpha\gamma)^{16}\text{O}$. In the first two papers, the detection both of gamma rays from this reaction and back-scattered particles made it possible to study, separately, the steering properties of the two sublattices in diatomic crystals. In the third paper the energy-loss of channeled protons was determined by detecting α -particles from this reaction. Using amorphous targets, the yield of the reaction was studied in the fourth paper. The second part consists of two papers dealing with imperfect crystals. In the first, the effects of mechanical treatment and in the second of radiation damage in the same diatomic materials as in part one were investigated by the channeling technique. The third part consists of two papers. In the first, the dechanneling of different species of ions in a tungsten crystal was investigated and in the second the channeling technique was used to study precipitated copper atoms in crystals of aluminium 4 wt.% copper alloy.

Preliminary reports on parts of this thesis were presented at the following meetings:

1. The International Conference on Atomic Collision Phenomena in Solids, University of Sussex, 1969.
2. Informal Symposium on Dechanneling, Aarhus University, 1970.

3. The International Conference on Atomic Collisions in Solids, Physics of Channeling and Related Phenomena, Gausdal, 1971.

After a general introduction, short reviews of the following papers constituting this thesis are given:

- I. R. Hellborg, Channeling studies in single crystals of calcium fluoride. *Physica Scripta* 3, 279 (1971).
- II. R. Hellborg, Depth and temperature dependence of the channeling effect in diatomic crystals. *Physica Scripta* 4, 203 (1971).
- III. R. Hellborg, The energy loss of channeled protons determined in an indirect way. *Physica Scripta* 4, 75 (1971).
- IV. R. Hellborg and L. Ask, The relative intensities and angular distributions of gamma rays from the nuclear reaction $^{19}\text{F}(\text{p}, \alpha\gamma)^{16}\text{O}$. *Physica Scripta* 6, 47 (1972).
- V. G. Skog and R. Hellborg, Channeling in single crystals with disordered surface layers. *Physica Scripta* 7, (1973).
- VI. R. Hellborg and G. Skog, Radiation damage in CaF_2 and BaF_2 investigated by the channeling technique. AE-474, AB Atomenergi, 1973.
- VII. R. Hellborg, Dechanneling of protons, ^3He - and ^4He -ions in tungsten, experimentally investigated. *Physica Scripta* 7, (1973).
- VIII. R. Hellborg, Structure changes during ageing in aluminium 4 wt.% copper alloy studied by the channeling technique. *Physica Scripta* 5, 219 (1972).

CHANNELING

Ever since the birth of modern atomic theory, experimental investigations of the interaction between charged particles and matter have been of increasing interest. Such studies have offered important tests of the gradually-refined models of atomic mechanisms. Moreover, the stopping of atomic particles has served as a spectroscopic tool within the field of nuclear physics. The access of particle accelerators has greatly increased the possibility of studying such interactions. The radiation damage problem in, for example, reactor design has raised technologically important questions on particle-solid interactions. The fundamental theoretical aspects of the scattering and stopping of energetic ions were surveyed by Bohr in his extensive work from 1948 [1]. Experimental and theoretical efforts have now resulted in a reasonable understanding of the slowing-down of ions in materials that can be regarded as a random system of atoms. Our theoretical and experimental knowledge about the passage of ions through matter has been reviewed many times, e.g. for light ions as protons and α -particles by Fano [2] and for heavy ions by Northcliffe [3].

New impetus to this field was given about a decade ago by the discovery that the penetration of energetic ions in a crystalline material exhibits a strong directional dependence, in that penetrating ions can be steered through the lattice by correlated collisions. In this process, the ions suffer a lower rate of energy-loss and are thus able to penetrate deeper into the material. Up until about 1962 calculations of stopping in solids were based on the slowing-down of ions in a series of independent collisions with a random arrangement of atoms. Agreement with experiment was sufficiently good so that any possible influence of the regular nature of the crystalline lattice was considered irrelevant. However, as experimental techniques improved, it became apparent that the penetration of ions into crystalline and amorphous solids showed slight

differences. In amorphous solids, the penetration profile exhibited an approximately Gaussian form as expected from theory, whereas polycrystalline samples invariably exhibited a skewness with a tail of deep penetration first observed by Davies et al. [4] in range studies of 40 keV ions in polycrystalline aluminium. At about the same time, experimenters measuring the sputtering ratio of single crystals of copper [5] reported unisotropic effects: when the ion beam was incident along a low index crystal direction, the sputtering ratio was found to show a minimum. This was tentatively interpreted in terms of what was called a "transparency model".

This led Robinson and Oen [6] to study the penetration of keV copper ions in regular crystalline lattices of copper by a high-speed digital computer. They observed some exceptionally long trajectories which apparently resulted from those atoms which travelled in a rather special way, such that their motion was constrained to within the open channels between adjacent close-packed rows. Furthermore this was not simply a transparency phenomenon, since these special atoms had their trajectories actually steered by a succession of glancing collisions with the channel walls. This phenomena has come to be called channeling. A trajectory which suffers only glancing collisions will be associated with a somewhat reduced rate of energy-loss, since the large angle collisions which account for a substantial fraction of energy loss are precluded. This immediately suggests that if a beam of energetic particles is incident close to a channeling direction of a single crystal target, increased penetration is to be expected. Furthermore, as the ions are constrained to within the open channels, the yield of head-on collisions with the lattice atoms will be drastically reduced. In fact, the concept of channeling was first envisaged as long ago as 1912 by J Stark [7], but during the next fifty years his ideas were not followed up and it was only by accident that they

were again brought to light.

Anomalous penetration effects were quickly observed even at considerably higher particle energies by Nelson and Thompson [8] and by Dearnaley [9] in proton transmission experiments. Domeij and Björkqvist [10] studied the anisotropy of α -particle emission from single crystals of tungsten, implanted with radioactive ^{222}Rn . The spatial distribution of emitted α -particles was measured and found to exhibit distinct dips in those directions corresponding to simple close-packed directions and planes. At about the same time, Gemmell and Holland [11] studied the wide angle scattering of 4 MeV protons from a single crystal of silicon. A particularly striking and useful feature of the channeling phenomena was studied at the University of Aarhus by Bøgh et al. [12] who confirmed the suggestion made by Lindhard [13], that close-encounter processes would be inhibited for channeled particles. A comprehensive theoretical framework for interpreting channeling studies was subsequently given by Lindhard in 1965 [14].

Numerous laboratories are now engaged in experimental and theoretical channeling investigations, involving a great variety of projectile and target combination and with energies from some keV to hundreds of MeV. The time elapsing since the discovery of channeling can roughly be divided into four partly overlapping periods:

1. The period of discovery from 1961 to 1965.
2. The period of understanding, from 1965 to 1968, initiated by Lindhard's extensive theoretical interpretation of the channeling process.
3. The period of application, from 1966, the extensive investigations on ion-implantation should especially be mentioned.

4. The period of quantitation, from 1969, with interest focused on topics such as depth dependence and the scattering process.

At the commencement of the work for this thesis, there had been several channeling studies in monatomic single crystals, whereas investigations in more complex crystals had been less frequent and none of them had permitted the separation of the effects from different sublattices. The purpose of the first papers was therefore to study the channeling effect in diatomic crystals and to measure independently the steering properties of each sublattice. Using crystals of CaF_2 , the steering of the heavy component sublattice was investigated in paper I using backscattering techniques, and the steering of the lighter component sublattice distinguished by detecting gamma-rays from the nuclear reaction $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$. As this reaction is resonant, with rather narrow resonances, the depth dependence could also be investigated. In paper II the measurements from paper I were extended and, in addition to crystals of CaF_2 , BaF_2 was also used. For the latter material, the amplitudes of the thermal vibrations of the two species of atoms over a large temperature interval can be obtained from neutron diffraction experiments. A strong depth dependence of the critical angle was observed and hence all measurements were made as a function of depth in the crystal and the values extrapolated to the surface to make comparison with calculated values possible. Papers I, II and III, the last of which investigated the energy-loss rate for channeled protons in BaF_2 and CaF_2 crystals were all experimentally performed during the years 1968 and 1969 and can be ascribed to period 2 in the rough schedule above.

During period 3, the channeling technique has above all been applied to the field of ion implantation and has been used to tackle one of the most important problems, namely the question of where the implanted atoms are physically located in the lattice [15]. The same measuring technique

10

as used in these ion-implantation investigations was also used in paper VIII to study precipitations of copper atoms in single crystals of aluminium 4 wt.% copper alloy aged in different ways.

Period 4 started when quantitative measurements became of importance, e.g. when the channeling effect was used in measurement of the lifetimes of compound nucleus states. This period like period 3, is still in progress. The depth dependence of the channeling effect, i.e. the scattering process in the crystal, is still a problem of present-day interest. Many of investigations of the dechanneling effect have recently been reported. In paper VII, the dechanneling in a tungsten crystal was studied with different species of ions, with ion energy and crystal temperature as parameters. Investigations of the disorder in, for example, implanted layers have recently been reported [16]. By assuming a simple model for the dechanneling process in the disordered layer, quantitative information about the defect was obtained. In papers V and VI, channeling in disordered crystals was investigated and qualitative values of the disorder were obtained by the same technique as used in [16].

SUMMARY

I. Channeling studies in single crystals of calcium fluoride.

Physica Scripta 3, 279 (1971).

The purpose of this paper was to study the channeling behaviour of protons and helium-ions in a diatomic crystal and to measure independently the steering properties of each sublattice. As this was the first in a series of investigations of the channeling effect the experimental facilities, the lattice structure of the crystal used as well as the method of crystal orientation and the technique of using Rutherford scattering and

the resonant nuclear reaction $^{19}\text{F}(\text{p}, \alpha\gamma)^{16}\text{O}$ were described in detail. The diatomic lattice of CaF_2 is a particularly interesting structure in the study of channeling since one may select a direction which consists of separate monatomic rows of each atomic sort or a direction which consists of identical rows all containing both species of atoms. To study the interaction with the Ca-sublattice, back-scattered ions were detected. To study the interaction of the ions with the F-sublattice, gamma-rays from the reaction $^{19}\text{F}(\text{p}, \alpha\gamma)^{16}\text{O}$ were detected. The width of the channeling dip at half value was studied with variation of different parameters such as species of ion, energy of ion, scattering depth in the crystal, interaction with the two sublattices and temperature of the crystal. It was found that the experimental width of the channeling dip has a functional dependence which agrees well with calculations based on the average potential along the row. However, the measured widths were lower in absolute magnitude than the calculated.

II. Depth and temperature dependence of the channeling effect in diatomic crystals.

Physica Scripta 4, 203 (1971).

The measurements initiated in paper I were extended in this paper with a systematic investigation of the depth and temperature dependence over a large temperature interval. The critical angle was studied for different close-packed axes in single crystals of CaF_2 and BaF_2 . The steering properties of each sublattice were measured independently by the same technique as used in paper I. The experimental values of the critical angle at the crystal surface were found to vary with temperature in agreement with calculations. Comparison in absolute values between the experimentally-found widths and calculations from an analytical formula given

by Barrett showed for the direction $\langle 111 \rangle$ with mixed rows the experimental values to be close to or slightly larger than the calculated. For the directions $\langle 110 \rangle$ and $\langle 100 \rangle$ which consist of pure rows, the interaction between the ions and the "heavy component rows" gave slightly larger values than those predicted. On the other hand, smaller values than those predicted were obtained for the interaction with the pure fluorine rows.

III. The energy-loss of channeled protons determined in an indirect way.
Physica Scripta 4, 75 (1971).

This paper describes a method of determining the rate of energy-loss of protons channeled along low index directions which subsequently escape. Back-scattered protons and α -particles from the same nuclear reaction as used in papers I and II were detected. The spectra of detected protons and α -particles are both dependent on the dechanneling rate and the energy-loss rate in the channel. By estimating a very simplified behaviour of the ions in the crystal, it was possible to extract from those two spectra the rate of energy-loss in the channel. The method was applied to different axes in CaF_2 and BaF_2 , i.e. the same crystals as used in paper II. Experimental values down to about 0.60 for the ratio of energy-loss rate in channel and random directions were found.

IV. The relative intensities and angular distributions of gamma-rays from the nuclear reaction $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$.
Physica Scripta 6, 47 (1972). (In collaboration with L. Ask.)

The relative intensities of the 6.13, 6.92 and 7.12 MeV gamma-rays from the nuclear reaction $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ were measured for proton energies

between 1.3 MeV and 2.2 MeV. In the same energy interval, angular distributions for the three gamma-rays were measured on and around the different resonances. At the time of the experiment, a new gamma-ray detecting system was used, viz a lithium-drifted germanium detector, permitting the two 7 MeV components to be fully resolved. The results of the measurements of the relative yields and angular distributions were used to obtain the integrated cross-section. The behaviour of the three components was found to differ somewhat at the various resonances. The experimental experience and the detailed knowledge of the reaction obtained during this investigation were of value during the work for papers I and II and information about the shape of the resonance peaks and the relative intensities of the different gamma-ray components was used in paper III.

V. Channeling in single crystals with disordered surface layers.

Physica Scripta 7, (1973). (In collaboration with G. Skog.)

In this paper channeling measurements performed with a CaF_2 crystal covered with different disordered surface layers is described. The disordered layers were obtained by incomplete surface treatments. Small angle scattering in the disordered layers introduces a broadening of the beam and consequently reduces the fraction of the beam along the aligned, crystal direction. By comparing the experimentally found values of the minimum yields with values calculated from angular distributions of the beam after passing through amorphous layers, the disordered surface layers have been assigned equivalent amorphous layer thicknesses. With this crystal material, even a mechanical polishing treatment with $0.1 \mu\text{m}$ abrasive particle size gives a disordered surface layer which is not acceptable for channeling measurements. By chemical etching, however, it seems possible to obtain a crystal surface which is acceptable.

VI. Radiation damage in CaF_2 and BaF_2 investigated by the channeling technique.

AE report 474 (1973) and accepted for publication in *Physica Scripta*.

(In collaboration with G. Skog.)

During the experiments for the preceding papers the crystals were observed to be damaged after some irradiation. This initiated the systematic investigation of radiation damage presented in the present paper. The formation of defects in single crystals of CaF_2 and BaF_2 due to room temperature bombardment with 2.0 MeV helium-ions was studied by the channeling technique. Aligned back-scattering spectra were taken after different doses of random irradiation. The measurements were made in different axial directions to give the possibility of observing a possible structure in the damage. A slight increase of the aligned yield with radiation dose was found for both species of crystals for doses below 10^{17} ions/cm². For CaF_2 at a dose of about 1.4×10^{17} ions/cm² a steep increase was found, after which the aligned yield saturated at a high value. Analysis of spectra measured along different aligned directions indicated that the structure of defects in CaF_2 and BaF_2 were different. From the experimental results, calculations based on single scattering theory giving the variation of the density of defect scattering centres with depth were made.

VII. Dechanneling of protons, ^3He - and ^4He -ions in tungsten.

Physica Scripta 7, (1973).

In this paper, a systematic investigation of the dechanneling rate of different ions in tungsten was made using the back-scattering technique. The energy and temperature dependence of the dechanneling rate was studied by protons and ^3He -ions in the energy range 1.0-4.5 MeV and with

^3He -ions in the energy range 1.5-9.0 MeV with incidence parallel to different close-packed axes and to the $\{110\}$ plane. The dechanneling rate was found to have an energy dependence described by E^{-1} for ^3He - and ^4He -ions in the axial case and also for protons in the planar case. However, for protons in the axial case the energy dependence was found to be weaker. A rather strong temperature dependence was found in the axial measurements, though not as strong as the suggested ρ^2 dependence. In the planar case, a weaker temperature dependence was found. Comparison with calculations based on the assumption of a steady increase in the transverse energy showed rough agreement in functional temperature dependence.

VIII. Structure changes during ageing in aluminium 4 wt.% copper alloy studied by the channeling technique.

Physica Scripta 5, 219 (1972).

By use of the channeling technique, an attempt to study the precipitation of copper atoms in single crystals of aluminium 4 wt.% copper alloy was made in this paper. It is known that during ageing of single crystals of this alloy, thin plates of CuAl_2 with diameters of some hundreds or thousands Ångström, but only some tens of atomic layers thick, precipitate. At first, the precipitations are coherent with the aluminium matrix but after more ageing they will grow and the tensions become so great that dislocations appear and the coherence partly disappears. It was found in this investigation that the stable phase θ gives an aligned yield in the back-scattering spectra quite different from the unstable phases proceeding θ . The channeling measurements were correlated with electron microscopy studies on the same ageing stages.

ACKNOWLEDGEMENT

During the performance of the work described in this thesis the author has been associated with two research institutions: AB Atomenergi, Studsvik, and Department of Nuclear Physics, University of Lund. It is a pleasure to acknowledge the support by the heads of these institutions: Prof. G. Holte at Studsvik and Profs. S. Johansson and B. Forkman at Lund.

It is my privilege to thank Dr. R. Pauli for his guidance and encouragement throughout this work. His full-hearted support and wide experience have been of great benefit.

I am greatly indebted to Dr. T. Wiedling for supplying the accelerator facilities at Studsvik.

Special thanks go to my co-authors, Dr. L. Ask and Fil.kand. G. Skog for their pleasant and stimulating cooperation, to Dr. J.U. Andersen for many fruitful discussions throughout the work, to Dr. J. Eriksson for help with computer calculations and to Prof. E. Möller who introduced me to the subject of channeling.

Thanks are also due to the members of the accelerator groups for their considerable technical support: P. Tykesson, B. Jonsson, L. Norell, L. Larsson and T. Larsson at Studsvik, and K. Håkansson at Lund.

W. Stany and G. Stålberg did excellent work in preparing and polishing the crystals used, for which the author is grateful.

I also wish to express sincere thanks to Miss B. Nygren for her untiring help in the preparation of many different manuscripts throughout the years.

REFERENCES

1. Bohr, N., Kgl. Dan. Vidensk. Selsk., Mat. Fys. Medd. 18, 8 (1948).
2. Fano, U., Ann. Rev. Nucl. Sci. 13, 1 (1963).
3. Northcliffe, L.C., Ann. Rev. Nucl. Sci. 13, 67 (1963).
4. Davies, J.A., Friesen, J., McIntyre, J.D., Can. J. Chem. 38, 1526 (1960).
5. e.g. Almèn, O., Bruce, G., Nucl. Instr. Meth. 11, 279 (1961).
6. Robinson, M.T., Oen, O.S., Appl. Phys. Lett. 2, 30 (1963).
7. Stark, J., Physik. Z. 13, 973 (1912).
8. Nelson, R.S., Thompson, M.W., Phil. Mag. 8, 1677 (1963).
9. Dearnaley, G., IEEE Trans. Nucl. Sci. NS-11 no. 3, 249 (1964).
10. Domeij, B., Björkqvist, K., Phys. Lett. 14, 127 (1965).
11. Gemmell, D.S., Holland, R.E., Phys. Rev. Lett. 14, 945 (1965).
12. Bøgh, E., Davies, J.A., Nielsen, K.O., Phys. Lett. 12, 129 (1964).
13. Lindhard, J., Phys. Lett. 12, 126 (1964).
14. Lindhard, J., Kgl. Dan. Vidensk. Selsk., Mat. Fys. Medd. 34, no. 14 (1965).
15. Mayer, J.W., Eriksson, L., Davies, J.A., Ion Implantation in Semiconductors (Academic Press, New York, 1970).
16. e.g. Westmoreland, J.E., Mayer, J.W., Eisen, F.H., Welsh, B., Radiat. Eff. 6, 161 (1970);
Feldman, L.C., Rodgers, J.W., J. Appl. Phys. 41, 3776 (1970).

